

NMSSM Higgs Discovery at the LHC *

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Abstract

We demonstrate that Higgs discovery at the LHC is possible in the context of the NMSSM even for those scenarios such that the only strongly produced Higgs boson is a very SM-like CP-even scalar which decays almost entirely to a pair of relatively light CP-odd states. In combination with other search channels, we are on the verge of demonstrating that detection of at least one of the NMSSM Higgs bosons is guaranteed at the LHC for accumulated luminosity of 300 fb^{-1} .

1. Introduction

One of the most attractive supersymmetric models is the Next to Minimal Supersymmetric Standard Model (NMSSM) (see [1,2] and references therein) which extends the MSSM by the introduction of just one singlet superfield, \hat{S} . When the scalar component of \hat{S} acquires a TeV scale vacuum expectation value (a very natural result in the context of the model), the superpotential term $\hat{S}\hat{H}_u\hat{H}_d$ generates an effective $\mu\hat{H}_u\hat{H}_d$ interaction for the Higgs doublet superfields. Such a term is essential for acceptable phenomenology. No other SUSY model generates this crucial component of the superpotential in as natural a fashion. Thus, the phenomenological implications of the NMSSM at future accelerators should be considered very seriously. One aspect of this is the fact that the h, H, A, H^\pm Higgs sector of the MSSM is extended so that there are three CP-even Higgs bosons ($h_{1,2,3}$, $m_{h_1} < m_{h_2} < m_{h_3}$), two CP-odd Higgs bosons ($a_{1,2}$, $m_{a_1} < m_{a_2}$) (we assume that CP is not violated in the Higgs sector) and a charged Higgs pair (h^\pm). An important question is then the extent to which the no-lose theorem for MSSM Higgs boson discovery at the LHC (after LEP constraints) is retained when going to the NMSSM; *i.e.* is the LHC guaranteed to find at least one of the $h_{1,2,3}$, $a_{1,2}$, h^\pm ? The first exploration of this issue appeared in [3], with the conclusion that for substantial portions of parameter space the LHC would be unable to detect any of the NMSSM Higgs bosons. Since then, there have been improvements in many of the detection modes and the addition of new ones. These will be summarized below and the implications reviewed. However, these improvements and additions do not address the possibly important $h \rightarrow aa$ type decays that could suppress all other types of signals [3,4].

One of the key ingredients in the no-lose theorem for MSSM Higgs boson discovery is the fact that relations among the Higgs boson masses are such that decays of the SM-like Higgs boson to AA are only possible if m_A is quite small, a region that is ruled out by LEP by virtue of the fact that $Z \rightarrow hA$ pair production was not detected despite the fact that the relevant coupling is large for small m_A . In the NMSSM, the lighter Higgs bosons, h_1 or h_2 , can be SM-like (in particular being the only Higgs with substantial WW/ZZ coupling) without the a_1 necessarily being heavy. In addition, this situation is not excluded by LEP searches for $e^+e^- \rightarrow Z^* \rightarrow h_{1,2}a_1$ since, in the NMSSM, the a_1 can have small Zh_2a_1 (Zh_1a_1) coupling when h_1 (h_2) is SM-like. [In addition, sum rules require that the Zh_1a_1 (Zh_2a_1) coupling is small when the h_1WW (h_2WW) couplings are near SM strength.] As a result, NMSSM parameters that are not excluded by current data can be chosen so that the $h_{1,2}$ masses are moderate in size ($\sim 100 - 130 \text{ GeV}$) and the $h_1 \rightarrow a_1a_1$ or $h_2 \rightarrow a_1a_1$ decays are dominant. Dominance

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of such decays falls outside the scope of the usual detection modes for the SM-like MSSM h on which the MSSM no-lose LHC theorem largely relies.

In Ref. [2], a partial no-lose theorem for NMSSM Higgs boson discovery at the LHC was established. In particular, it was shown that the LHC would be able to detect at least one of the Higgs bosons (typically, one of the lighter CP-even Higgs states) throughout the full parameter space of the model, excluding only those parameter choices for which there is sensitivity to the model-dependent decays of Higgs bosons to other Higgs bosons and/or superparticles. Here, we will address the question of whether or not this no-lose theorem can be extended to those regions of NMSSM parameter space for which Higgs bosons can decay to other Higgs bosons. We find that the parameter choices such that the “standard” discovery modes fail *would* allow Higgs boson discovery if detection of $h \rightarrow aa$ decays is possible. (When used generically, the symbol h will now refer to $h = h_1, h_2$ or h_3 and the symbol a will refer to $a = a_1$ or a_2). Detection of $h \rightarrow aa$ will be difficult since each a will decay primarily to $b\bar{b}$ (or 2 jets if $m_a < 2m_b$), $\tau^+\tau^-$, and, possibly, $\tilde{\chi}_1^0\tilde{\chi}_1^0$, yielding final states that will typically have large backgrounds at the LHC.

In [2] we scanned the parameter space, removing parameter choices ruled out by constraints from LEP on Higgs boson production, $e^+e^- \rightarrow Zh$ or $e^+e^- \rightarrow ha$ [5], and eliminating parameter choices for which one Higgs boson can decay to two other Higgs bosons or a vector boson plus a Higgs boson. For the surviving regions of parameter space, we estimated the statistical significances ($N_{SD} = S/\sqrt{B}$) for all Higgs boson detection modes so far studied at the LHC [6–9]. These are (with $\ell = e, \mu$)

- 1) $gg \rightarrow h/a \rightarrow \gamma\gamma$;
- 2) associated Wh/a or $t\bar{t}h/a$ production with $\gamma\gamma\ell^\pm$ in the final state;
- 3) associated $t\bar{t}h/a$ production with $h/a \rightarrow b\bar{b}$;
- 4) associated $b\bar{b}h/a$ production with $h/a \rightarrow \tau^+\tau^-$;
- 5) $gg \rightarrow h \rightarrow ZZ^{(*)} \rightarrow 4$ leptons;
- 6) $gg \rightarrow h \rightarrow WW^{(*)} \rightarrow \ell^+\ell^-\nu\bar{\nu}$;
- 7) $WW \rightarrow h \rightarrow \tau^+\tau^-$;
- 8) $WW \rightarrow h \rightarrow WW^{(*)}$.

For an integrated luminosity of 300 fb^{-1} at the LHC, all the surviving points yielded $N_{SD} > 10$ after combining all modes, including the W -fusion modes. Thus, NMSSM Higgs boson discovery by just one detector with $L = 300 \text{ fb}^{-1}$ is essentially guaranteed for those portions of parameter space for which Higgs boson decays to other Higgs bosons or supersymmetric particles are kinematically forbidden.

In this work, we investigate the complementary part of the parameter space, where *at least one* Higgs boson decays to other Higgs bosons. To be more precise, we require at least one of the following decay modes to be kinematically allowed:

$$\begin{aligned} & i) h \rightarrow h'h', \quad ii) h \rightarrow aa, \quad iii) h \rightarrow h^\pm h^\mp, \quad iv) h \rightarrow aZ, \\ & v) h \rightarrow h^\pm W^\mp, \quad vi) a' \rightarrow ha, \quad vii) a \rightarrow hZ, \quad viii) a \rightarrow h^\pm W^\mp. \end{aligned} \quad (1)$$

After searching those regions of parameter space for which one or more of the decays $i) - viii)$ is allowed, we found that the only subregions for which discovery of a Higgs boson in modes 1) – 8) was not possible correspond to NMSSM parameter choices for which (a) there is a light CP-even Higgs boson with substantial doublet content that decays mainly to two still lighter CP-odd Higgs states, $h \rightarrow aa$, and (b) all the other Higgs states are either dominantly singlet-like, implying highly suppressed production rates, or relatively heavy, decaying to $t\bar{t}$, to one of the “difficult” modes $i) - viii)$ or to a pair of sparticles. In such cases, the best opportunity for detecting at least one of the NMSSM Higgs bosons is to employ $WW \rightarrow h$ production and develop techniques for extracting a signal for the $h \rightarrow aa \rightarrow jj\tau^+\tau^-$ (including $jj = b\bar{b}$) process. We have performed a detailed simulation of the $aa \rightarrow jj\tau^+\tau^-$ final state and find that its detection may be possible after accumulating 300 fb^{-1} in both the ATLAS and CMS detectors.

2. The model and scanning procedures

We consider the simplest version of the NMSSM [1], where the term $\mu \hat{H}_1 \hat{H}_2$ in the superpotential of the MSSM is replaced by (we use the notation \hat{A} for the superfield and A for its scalar component field)

$$\lambda \hat{H}_1 \hat{H}_2 \hat{S} + \frac{\kappa}{3} \hat{S}^3, \quad (2)$$

so that the superpotential is scale invariant. We make no assumption on “universal” soft terms. Hence, the five soft supersymmetry breaking terms

$$m_{H_1}^2 H_1^2 + m_{H_2}^2 H_2^2 + m_S^2 S^2 + \lambda A_\lambda H_1 H_2 S + \frac{\kappa}{3} A_\kappa S^3 \quad (3)$$

are considered as independent. The masses and/or couplings of sparticles will be such that their contributions to the loop diagrams inducing Higgs boson production by gluon fusion and Higgs boson decay into $\gamma\gamma$ are negligible. In the gaugino sector, we chose $M_2 = 1$ TeV (at low scales). Assuming universal gaugino masses at the coupling constant unification scale, this yields $M_1 \sim 500$ GeV and $M_3 \sim 3$ TeV. In the squark sector, as particularly relevant for the top squarks which appear in the radiative corrections to the Higgs potential, we chose the soft masses $m_Q = m_T \equiv M_{\text{susy}} = 1$ TeV, and varied the stop mixing parameter

$$X_t \equiv 2 \frac{A_t^2}{M_{\text{susy}}^2 + m_t^2} \left(1 - \frac{A_t^2}{12(M_{\text{susy}}^2 + m_t^2)} \right). \quad (4)$$

As in the MSSM, the value $X_t = \sqrt{6}$ – so called maximal mixing – maximizes the radiative corrections to the Higgs boson masses, and we found that it leads to the most challenging points in the parameter space of the NMSSM. We adopt the convention $\lambda, \kappa > 0$, in which $\tan \beta$ can have either sign. We require $|\mu_{\text{eff}}| > 100$ GeV; otherwise a light chargino would have been detected at LEP. The only possibly light SUSY particle will be the $\tilde{\chi}_1^0$. A light $\tilde{\chi}_1^0$ is a frequent characteristic of parameter choices that yield a light a_1 .

We have performed a numerical scan over the free parameters. For each point, we computed the masses and mixings of the CP-even and CP-odd Higgs bosons, h_i ($i = 1, 2, 3$) and a_j ($j = 1, 2$), taking into account radiative corrections up to the dominant two loop terms, as described in [10]. We eliminated parameter choices excluded by LEP constraints [5] on $e^+e^- \rightarrow Zh_i$ and $e^+e^- \rightarrow h_i a_j$. The latter provides an upper bound on the $Zh_i a_j$ reduced coupling, R'_{ij} , as a function of $m_{h_i} + m_{a_j}$ for $m_{h_i} \simeq m_{a_j}$. Finally, we calculated m_{h^\pm} and required $m_{h^\pm} > 155$ GeV, so that $t \rightarrow h^\pm b$ would not be seen.

In order to probe the complementary part of the parameter space as compared to the scanning of Ref. [2], we required that at least one of the decay modes $i) - v\bar{v}$ is allowed. For each Higgs state, we calculated all branching ratios including those for modes $i) - v\bar{v}$, using an adapted version of the FORTRAN code HDECAY [11]. We then estimated the expected statistical significances at the LHC in all Higgs boson detection modes 1) – 8) by rescaling results for the SM Higgs boson and/or the MSSM h, H and/or A . The rescaling factors are determined by R_i, t_i and $b_i = \tau_i$, the ratios of the $VVh_i, t\bar{t}h_i$ and $b\bar{b}h_i, \tau^+\tau^-h_i$ couplings, respectively, to those of a SM Higgs boson. Of course $|R_i| < 1$, but t_i and b_i can be larger, smaller or even differ in sign with respect to the SM. For the CP-odd Higgs bosons, $R'_i = 0$ at tree-level; t'_j and b'_j are the ratios of the $i\gamma_5$ couplings for $t\bar{t}$ and $b\bar{b}$, respectively, relative to SM-like strength. A detailed discussion of the procedures for rescaling SM and MSSM simulation results for the statistical significances in channels 1) – 8) will appear elsewhere.

In our set of randomly scanned points, we selected those for which all the statistical significances in modes 1) – 8) are below 5σ . We obtained a lot of points, all with similar characteristics. Namely, in the Higgs spectrum, we always have a very SM-like CP-even Higgs boson with a mass between 115 and 135 GeV (*i.e.* above the LEP limit), which can be either h_1 or h_2 , with a reduced coupling to the gauge bosons $R_1 \simeq 1$ or $R_2 \simeq 1$, respectively. This state decays dominantly to a pair of (very) light CP-odd

Point Number	1	2	3	4	5	6
Bare Parameters						
λ	0.2872	0.2124	0.3373	0.3340	0.4744	0.5212
κ	0.5332	0.5647	0.5204	0.0574	0.0844	0.0010
$\tan \beta$	2.5	3.5	5.5	2.5	2.5	2.5
μ_{eff} (GeV)	200	200	200	200	200	200
A_λ (GeV)	100	0	50	500	500	500
A_κ (GeV)	0	0	0	0	0	0
CP-even Higgs Boson Masses and Couplings						
m_{h_1} (GeV)	115	119	123	76	85	51
R_1	1.00	1.00	-1.00	0.08	0.10	-0.25
t_1	0.99	1.00	-1.00	0.05	0.06	-0.29
b_1	1.06	1.05	-1.03	0.27	0.37	0.01
Relative gg Production Rate	0.97	0.99	0.99	0.00	0.01	0.08
$BR(h_1 \rightarrow b\bar{b})$	0.02	0.01	0.01	0.91	0.91	0.00
$BR(h_1 \rightarrow \tau^+\tau^-)$	0.00	0.00	0.00	0.08	0.08	0.00
$BR(h_1 \rightarrow a_1 a_1)$	0.98	0.99	0.98	0.00	0.00	1.00
m_{h_2} (GeV)	516	626	594	118	124	130
R_2	-0.03	-0.01	0.01	-1.00	-0.99	-0.97
t_2	-0.43	-0.30	-0.10	-0.99	-0.99	-0.95
b_2	2.46	-3.48	3.44	-1.03	-1.00	-1.07
Relative gg Production Rate	0.18	0.09	0.01	0.98	0.99	0.90
$BR(h_2 \rightarrow b\bar{b})$	0.01	0.04	0.04	0.02	0.01	0.00
$BR(h_2 \rightarrow \tau^+\tau^-)$	0.00	0.01	0.00	0.00	0.00	0.00
$BR(h_2 \rightarrow a_1 a_1)$	0.04	0.02	0.83	0.97	0.98	0.96
m_{h_3} (GeV)	745	1064	653	553	554	535
CP-odd Higgs Boson Masses and Couplings						
m_{a_1} (GeV)	56	7	35	41	59	7
t'_1	0.05	0.03	0.01	-0.03	-0.05	-0.06
b'_1	0.29	0.34	0.44	-0.20	-0.29	-0.39
Relative gg Production Rate	0.01	0.03	0.05	0.01	0.01	0.05
$BR(a_1 \rightarrow b\bar{b})$	0.92	0.00	0.93	0.92	0.92	0.00
$BR(a_1 \rightarrow \tau^+\tau^-)$	0.08	0.94	0.07	0.07	0.08	0.90
m_{a_2} (GeV)	528	639	643	560	563	547
Charged Higgs Mass (GeV)	528	640	643	561	559	539
Most Visible of the LHC Processes 1)-8)	2 (h_1)	2 (h_1)	8 (h_1)	2 (h_2)	8 (h_2)	8 (h_2)
$N_{SD} = S/\sqrt{B}$ Significance of this process at $L=300 \text{ fb}^{-1}$	0.48	0.26	0.55	0.62	0.53	0.16
$N_{SD}(L=300 \text{ fb}^{-1})$ for $WW \rightarrow h \rightarrow aa \rightarrow jj\tau^+\tau^-$ at LHC	50	22	69	63	62	21

Table 1: Properties of selected scenarios that could escape detection at the LHC. In the table, $R_i = g_{h_i VV}/g_{h_{SM} VV}$, $t_i = g_{h_i t\bar{t}}/g_{h_{SM} t\bar{t}}$ and $b_i = g_{h_i b\bar{b}}/g_{h_{SM} b\bar{b}}$ for $m_{h_{SM}} = m_{h_i}$; t'_1 and b'_1 are the $i\gamma_5$ couplings of a_1 to $t\bar{t}$ and $b\bar{b}$ normalized relative to the scalar $t\bar{t}$ and $b\bar{b}$ SM Higgs couplings. We also give the gg fusion production rate ratio, $gg \rightarrow h_i/gg \rightarrow h_{SM}$, for $m_{h_{SM}} = m_{h_i}$. Important absolute branching ratios are displayed. For points 2 and 6, the decays $a_1 \rightarrow jj$ ($j \neq b$) have $BR(a_1 \rightarrow jj) \simeq 1 - BR(a_1 \rightarrow \tau^+\tau^-)$. For the heavy h_3 and a_2 , we give only their masses. For all points 1 – 6, the statistical significances for the detection of any Higgs boson in any of the channels 1) – 8) are tiny; the next-to-last row gives their maximum together with the process number and the corresponding Higgs state. The last row gives the statistical significance of the new $WW \rightarrow h \rightarrow aa \rightarrow jj\tau^+\tau^-$ [$h = h_1$ ($h = h_2$) for points 1–3 (4–6)] LHC signal explored here.

states, $a_1 a_1$, with m_{a_1} between 5 and 65 GeV. The singlet component of a_1 cannot be dominant if we are to have a large $h_1 \rightarrow a_1 a_1$ or $h_2 \rightarrow a_1 a_1$ branching ratio when the h_1 or h_2 , respectively, is the SM-like Higgs boson. Further, when the h_1 or h_2 is very SM-like, one has small $Z h_1 a_1$ or $Z h_2 a_1$ coupling, respectively, so that $e^+ e^- \rightarrow h_1 a_1$ or $e^+ e^- \rightarrow h_2 a_1$ associated production places no constraint on the light CP-odd state at LEP. We have selected six difficult benchmark points, displayed in Table 1. These are such that $a_1 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ decays are negligible or forbidden. (Techniques for cases such that $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ decay modes are important are under development.) For points 1 – 3, h_1 is the SM-like CP-even state, while for points 4 – 6 it is h_2 . We have selected the points so that there is some variation in the $h_{1,2}$ and a_1 masses. The main characteristics of the benchmark points are displayed in Table 1. Note the large $BR(h \rightarrow a_1 a_1)$ of the SM-like h ($h = h_1$ for points 1 – 3 and $h = h_2$ for points 4 – 6). For points 4 – 6, with $m_{h_1} < 100$ GeV, the h_1 is mainly singlet. As a result, the $Z h_1 a_1$ coupling is very small, implying no LEP constraints on the h_1 and a_1 from $e^+ e^- \rightarrow h_1 a_1$ production.

We note that in the case of the points 1 – 3, the h_2 would not be detectable either at the LHC or at a Linear Collider (LC). For points 4 – 6, the h_1 , though light, is singlet in nature and would not be detectable. Further, the h_3 or a_2 will only be detectable for points 1 – 6 if a super high energy LC is eventually built so that $e^+ e^- \rightarrow Z \rightarrow h_3 a_2$ is possible. Thus, we will focus on searching for the SM-like h_1 (h_2) for points 1 – 3 (4 – 6) using the dominant h_1 (h_2) $\rightarrow a_1 a_1$ decay mode.

In the case of points 2 and 6, the $a_1 \rightarrow \tau^+ \tau^-$ decays are dominant. The final state of interest will be $jj\tau^+ \tau^-$, where the jj actually comes primarily from $a_1 a_1 \rightarrow \tau^+ \tau^- \tau^+ \tau^-$ followed by jet decays of two of the τ 's: $\tau^+ \tau^- \rightarrow jj + \nu's$. (The contribution from direct $a_1 \rightarrow jj$ decays to the $jj\tau^+ \tau^-$ final state is relatively small for points 2 and 6.) In what follows, when we speak of $\tau^+ \tau^-$, we refer to those τ 's that are seen in the $\tau^+ \tau^- \rightarrow \ell^+ \ell^- + \nu's$ final state ($\ell = e, \mu$). For points 1 and 3 – 5 $BR(a_1 \rightarrow b\bar{b})$ is substantial. The relevant final state is $b\bar{b}\tau^+ \tau^-$. Nonetheless, we begin with a study of the backgrounds and signals without requiring b -tagging. With our latest cuts, we will see that b -tagging is not necessary to overcome the apriori large Drell-Yan $\tau^+ \tau^-$ + jets background. It is eliminated by stringent cuts for finding the highly energetic forward / backward jets characteristic of the WW the fusion process. As a result, we will find good signals for all 6 of our points.

In principle, one could explore final states other than $b\bar{b}\tau^+ \tau^-$ (or $jj\tau^+ \tau^-$ for points 2 and 6). However, all other channels will be much more problematical at the LHC. A $4b$ -signal would be burdened by a large QCD background even after implementing b -tagging. A $4j$ -signal would be completely swamped by QCD background. Meanwhile, the 4τ -channel (by which we mean that all taus decay leptonically) would not allow one to reconstruct the h_1, h_2 resonances.

In the case of the $2b2\tau$ (or $2j2\tau$) signature, we identify the τ 's through their leptonic decays to electrons and muons. Thus, they will yield some amount of missing (transverse) momentum, p_{miss}^T . This missing transverse momentum can be projected onto the visible e, μ -momenta in an attempt to reconstruct the parent τ -direction.

3. Monte Carlo Results for the LHC

Let us now focus on the $WW \rightarrow h \rightarrow aa$ channel that we believe provides the best hope for Higgs detection in these difficult NMSSM cases. (We reemphasize that the h_1 [cases 1 – 3] or h_2 [cases 4 – 6] has nearly full SM strength coupling to WW .) The $b\bar{b}\tau^+ \tau^-$ (or $2j\tau^+ \tau^-$, for points 2 and 6) final state of relevance is complex and subject to large backgrounds, and the a_1 masses of interest are very modest in size. In order to extract the WW fusion $2j2\tau$ NMSSM Higgs boson signature, it is crucial to strongly exploit forward and backward jet tagging on the light quarks emerging after the double W -strahlung preceding WW -fusion. We also require two additional central jets (from one of the a 's) and two opposite sign central leptons ($\ell = e, \mu$) coming from the $\tau^+ \tau^-$ emerging from the decay of the other a . By imposing stringent forward / backward jet tagging cuts, we remove the otherwise very large background from Drell-Yan $\tau^+ \tau^-$ + jets production. In the end, the most important background is due to $t\bar{t}$ production and decay via the purely SM process, $gg \rightarrow t\bar{t} \rightarrow b\bar{b}W^+ W^- \rightarrow b\bar{b}\tau^+ \tau^- + p_{\text{miss}}^T$, in

association with forward and backward jet radiation.

We have employed numerical simulations based on a version of HERWIG v6.4 [12–14] modified to allow for appropriate NMSSM couplings and decay rates. Calorimeter emulation was performed using the GETJET code [15]. Since the a_1 will not have been detected previously, we must assume a value for m_{a_1} . In dealing with actual experimental data, it will be necessary to repeat the analysis for densely spaced m_{a_1} values and look for the m_{a_1} choice that produces the best signal. We look among the central jets for the combination with invariant mass M_{jj} closest to m_{a_1} . In Fig. 1, we show the $M_{jj\tau^+\tau^-}$ invariant mass distribution obtained after cuts, but before b -tagging or inclusion of K factors — the plot presented assumes that we have hit on the correct m_{a_1} choice.

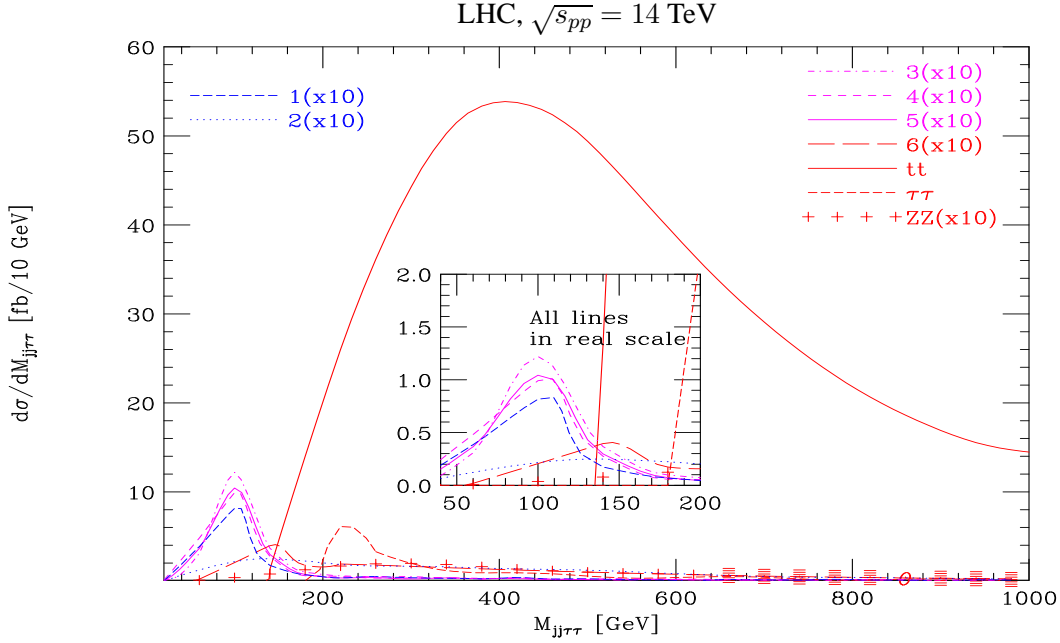


Fig. 1: We plot $d\sigma/dM_{jj\tau^+\tau^-}$ [fb/10 GeV] vs $M_{jj\tau^+\tau^-}$ [GeV] for signals and backgrounds after basic event selections, but before b tagging. The lines corresponding to points 4 and 5 are visually indistinguishable. No K factors are included.

The selection strategy adopted is a more refined (as regards forward / backward jet tagging) version of that summarized in [16]. It is clearly efficient in reconstructing the h_1 (for points 1–3) and h_2 (for points 4–6) masses from the $jj\tau^+\tau^-$ system, as one can appreciate by noting the peaks appearing at $M_{jj\tau^+\tau^-} \approx 100$ GeV. In contrast, the heavy Higgs resonances at m_{h_2} for points 1–3 and the rather light resonances at m_{h_1} for points 4–6 (recall Table 1) do not appear, the former mainly because of the very poor production rates and the latter due to the fact that either the $h_1 \rightarrow a_1 a_1$ decay mode is not open (points 4, 5) or – if it is – the jets and e/μ -leptons eventually emerging from the a_1 decays are too soft to pass the acceptance cuts (point 6, for which $m_{a_1} = 7$ GeV and $m_{h_1} = 51$ GeV). For all six NMSSM setups, the Higgs resonance produces a bump below the end of the low mass tail of the $t\bar{t}$ background (see the insert in Fig. 1). Note how small the DY $\tau^+\tau^-$ background is after strong forward / backward jet tagging. Since the main surviving background is from $t\bar{t}$ production, b tagging is not helpful. For points 2 and 6, for which the signal has no b 's in the final state, anti- b -tagging might be useful, but has not been considered here.

To estimate S/\sqrt{B} , we assume $L = 300 \text{ fb}^{-1}$, a K factor of 1.1 for the WW fusion signal and K factors of 1, 1 and 1.6 for the DY $\tau^+\tau^-$, ZZ production and $t\bar{t}$ backgrounds, respectively. (These K factors are not included in the plot of Fig. 1.) We sum events over the region $40 \leq M_{jj\tau^+\tau^-} \leq$

150 GeV. (Had we only included masses below 130 GeV, we would have had no $t\bar{t}$ background, and the S/\sqrt{B} values would be enormous. However, we are concerned that this absence of $t\bar{t}$ background below 130 GeV might be a reflection of limited Monte Carlo statistics. As a result we have taken the more conservative approach of at least including the first few bins for which our Monte Carlo does predict some $t\bar{t}$ background.)

For points 1, 2, 3, 4, 5 and 6, we obtain signal rates of about $S = 1636, 702, 2235, 2041, 2013$, and 683, respectively. The $t\bar{t}$ +jets background rate is $B_{t\bar{t}} \sim 795$. The ZZ background rate is $B_{ZZ} \sim 6$. The DY $\tau^+\tau^-$ background rate is negligible. (We are continuing to increase our statistics to get a fully reliable estimate.) The resulting $N_{SD} = S/\sqrt{B}$ values for points 1-6 are 50, 22, 69, 63, 62, and 21, respectively. The smaller values for points 2 and 6 are simply a reflection of the difficulty of isolating and reconstructing the two jets coming from the decay of a very light a_1 . Overall, these preliminary results are very encouraging and suggest that a no-lose theorem for NMSSM Higgs detection at the LHC is close at hand.

4. Conclusions

In summary, we have obtained a statistically very significant LHC signal in the $jj\tau^+\tau^-$ final state of WW fusion for cases in which the NMSSM parameters are such that the most SM-like of the CP-even Higgs bosons, h , is relatively light and decays primarily to a pair of CP-odd Higgs states, $h \rightarrow aa$ with $a \rightarrow b\bar{b}, \tau^+\tau^-$ if $m_a > 2m_b$ or $a \rightarrow jj, \tau^+\tau^-$ if $m_a < 2m_b$. The statistical significances are (at least) of order 50 to 70 for points with $m_a > 2m_b$ and of order 20 for points with $m_a < 2m_b$. These high significances were obtained by imposing stringent cuts requiring highly energetic forward/backward jets in order to isolate the WW fusion signal process from backgrounds such as DY $\tau^+\tau^-$ pair production. Still, this signal will be the only evidence for Higgs bosons at the LHC. A future LC will probably be essential in order to confirm that the enhancement seen at the LHC really does correspond to a Higgs boson. At the LC, discovery of a light SM-like h is guaranteed to be possible in the Zh final state using the recoil mass technique [17].

In the present study, we have not explored the cases in which the $a_1 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ decay has a large branching ratio. Detecting a Higgs signal in such cases will require a rather different procedure. Work on the $WW \rightarrow h \rightarrow$ invisible signal is in progress [18].

As we have stressed, for parameter space points of the type we have discussed here, detection of any of the other MSSM Higgs bosons is likely to be impossible at the LHC and is likely to require an LC with $\sqrt{s_{e^+e^-}}$ above the relevant thresholds for $h'a'$ production, where h' and a' are heavy CP-even and CP-odd Higgs bosons, respectively.

Although results for the LHC indicate that Higgs boson discovery will be possible for the type of situations we have considered, it is clearly important to refine and improve the techniques for extracting a signal. This will almost certainly be possible once data is in hand and the $t\bar{t}$ background can be more completely modeled.

Clearly, if SUSY is discovered and $WW \rightarrow WW$ scattering is found to be perturbative at WW energies of 1 TeV (and higher), and yet no Higgs bosons are detected in the standard MSSM modes, a careful search for the signal we have considered should have a high priority.

Finally, we should remark that the $h \rightarrow aa$ search channel considered here in the NMSSM framework is also highly relevant for a general two-Higgs-doublet model, 2HDM. It is really quite possible that the most SM-like CP-even Higgs boson of a 2HDM will decay primarily to two CP-odd states. This is possible even if the CP-even state is quite heavy, unlike the NMSSM cases considered here. If CP violation is introduced in the Higgs sector, either at tree-level or as a result of one-loop corrections (as, for example, is possible in the MSSM), $h \rightarrow h'h''$ decays will generally be present. The critical signal will be the same as that considered here.

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